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Environmental impact trade-offs in diet formulation for broiler production systems in the UK and US

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ABSTRACT

The environmental impacts associated with broiler production arise mainly from the production and consumption of feed. The aim was to develop a tool for formulating broiler diets designed to target and reduce individually specific environmental impact categories in two contrasting regions, the UK and US. Using linear programming, least cost broiler diets were formulated for each region, using the most common genotype specific to each region. The environmental impact of the systems was defined using 6 categories calculated through a Life Cycle Assessment (LCA) method: global warming potential (GWP), fresh water eutrophication potential (FWEP), marine eutrophication potential (MEP), terrestrial acidification potential (TAP), non-renewable energy use (NREU) and agricultural land use (ALU). Diets were then formulated for each region to minimise each impact category, without compromising bird performance. The diets formulated for environmental impact objectives increased their cost in most cases by between 20 and 30% (the cost increase limit), with the exception of the least GWP (+16%) and the least NREU (+4%) diets in the UK, and the least TAP diet in the US (+14%). The degree of flexibility to reduce simultaneously several environmental impact categories in the UK and the US differed due to the different feed ingredients available to each region. The results suggested there was potential to minimise several impact categories simultaneously by reducing the impact of one impact category compared to least cost, through diet formulation in the UK; this was shown to a greater and lesser extent in the least FWEP and the least NREU diet formulations respectively. In the US, there was no way to minimise one impact category through diet formulation without increasing other impact categories caused by the

system. Employing a multi-criteria approach to diet formulation methodologies, where environmental impact as well as economic implications are considered, will form an important pillar in broader efforts to improve the sustainability of animal production.

Key words: Poultry; Broilers; Diet Formulation; Life Cycle Assessment; Environmental Impact Mitigation

1. Introduction

Global poultry meat production grew by 104% between 1990 and 2012 (FAO, 2016) and is predicted to become soon the world's most consumed form of animal protein (OECD/FAO, 2014). The increased importance of global sustainability in food production fits well with the progress made within the poultry industry, which currently has relatively low environmental impacts when compared to other livestock sectors (Williams et al., 2006). This progress can be attributed to improvements made in the production systems, but is mainly due to artificial selection for improved energy use efficiency (Faraday, 2007, Laughlin, 2007, Zuidhof et al., 2014, Tallentire et al., 2016). Despite its production being amongst the least environmentally impacting livestock commodities produced in the EU and North America, widespread consumption of poultry products means that further improvements are important and should still be made (Leinonen et al., 2013, MacLeod et al., 2013, Nastasijevic et al., 2015).

As the environmental impacts associated with broiler chicken production arise mainly from the provision and consumption of feed, it is logical to focus on diet formulation and feed ingredient choice in order to mitigate these impacts (Pelletier, 2008, Boggia et al., 2010, Leinonen et al., 2012, 2013). For broiler systems, focusing only on global warming potential (GWP) would not be sufficient. Due to their reliance on high protein diets, broiler chicken production is associated with high eutrophication (EP), acidification potentials (AP) and agricultural land use (ALU) (Sutton et al., 2008, Boggia et al., 2010). The majority of the AP and EP caused by broiler production is due to emissions during manure storage and application, as a direct result of the birds' N and P excretion.

The objective of this study was to develop a methodology which enabled broiler diets to be formulated explicitly for different environmental impact objectives and apply it to poultry production systems in two different world regions. A novel methodology was developed to formulate diets for reduced impact in specific environmental categories, while not penalising bird growth, by applying a Life Cycle Assessment (LCA) approach integrated into a mechanistic diet formulation tool. Environmental impacts caused by both feed production and nutrient excretion associated with each diet had to be accounted for. The consequences of formulating diets for least impact in one environmental category on the other environmental impact categories and cost were investigated. Broilers are fed diets based on very different dietary ingredients in the EU and North America, either because of legislation, trade agreements or climatic conditions, so the opportunities for reduction in specific environmental impact categories may be expected to differ between the two regions (Kebreab et al., 2016). The UK, which represents 12% of broiler meat production in the EU (European Commission, 2014, The Poultry Site, 2014), was used to represent production in Europe. The top three broiler meat producing regions in North America are the states of Georgia, Arkansas and Alabama (National Chicken Council, 2012b); therefore the south-eastern states of the US were used to represent the North American broiler systems.

2. Method

2.1. Goal, scope and model structure

A LCA methodology was integrated with a diet formulation tool with the goal of investigating the potential for reducing the environmental impacts associated with the production of broiler chicken meat via changes in their diet in the UK and US. The system considered was conventional indoor broiler production (Figure 1), which is the predominant broiler production system in both regions (The British Poultry Council, 2016, National Chicken Council, 2012a), from cradle to farm gate. The functional unit was the growth of one metric tonne of broiler live weight. The average broiler was raised to a slaughter weight of 2.2 kg in the UK poultry systems (Defra, 2014b) and 2.8 kg in the US poultry systems (National Chicken Council, 2016). This took 36 and 44 days respectively based on average as-hatched performance objectives for the corresponding breeds raised in each region (Aviagen, 2014b, 2014d). The broiler strains considered here were the 2014 Ross 308 and Ross 708. The fast growing Ross 308 strain is used widely in Europe, and therefore was considered appropriate for the purposes of this study to represent UK systems (Borck Høg et al., 2011). The US market is dominated by high meat yielding strains, such as the Ross 708, driven by the demand for high breast meat yield (Dozier and Gehring, 2014). Each breed had its own unique nutritional requirements, hence three and four growth phases of broiler production were modelled for the UK and the US systems respectively; diets were specifically formulated to meet the growth requirements of the birds during each phase in accordance with nutritional requirements (Tables S1 and S2 in the supplementary material), outlined in the nutrition specification manuals (Aviagen, 2014a, 2014c). The phases were as follows: the starter phase (hatching - day 10); the grower phase (day 11 - 24); the finisher phase (day 25 - 39 or slaughter, i.e. in the UK); and the withdrawal phase, from day 39 until slaughter (US only). Upstream inputs, such as those associated with feed production, transportation and resource use in the growing facilities were all included within the boundaries of this analysis. The waste produced during production was also included within the boundaries of the LCA; however actual burdens of slaughter and process losses that can occur between the farm gate and the end of the processing line were excluded.

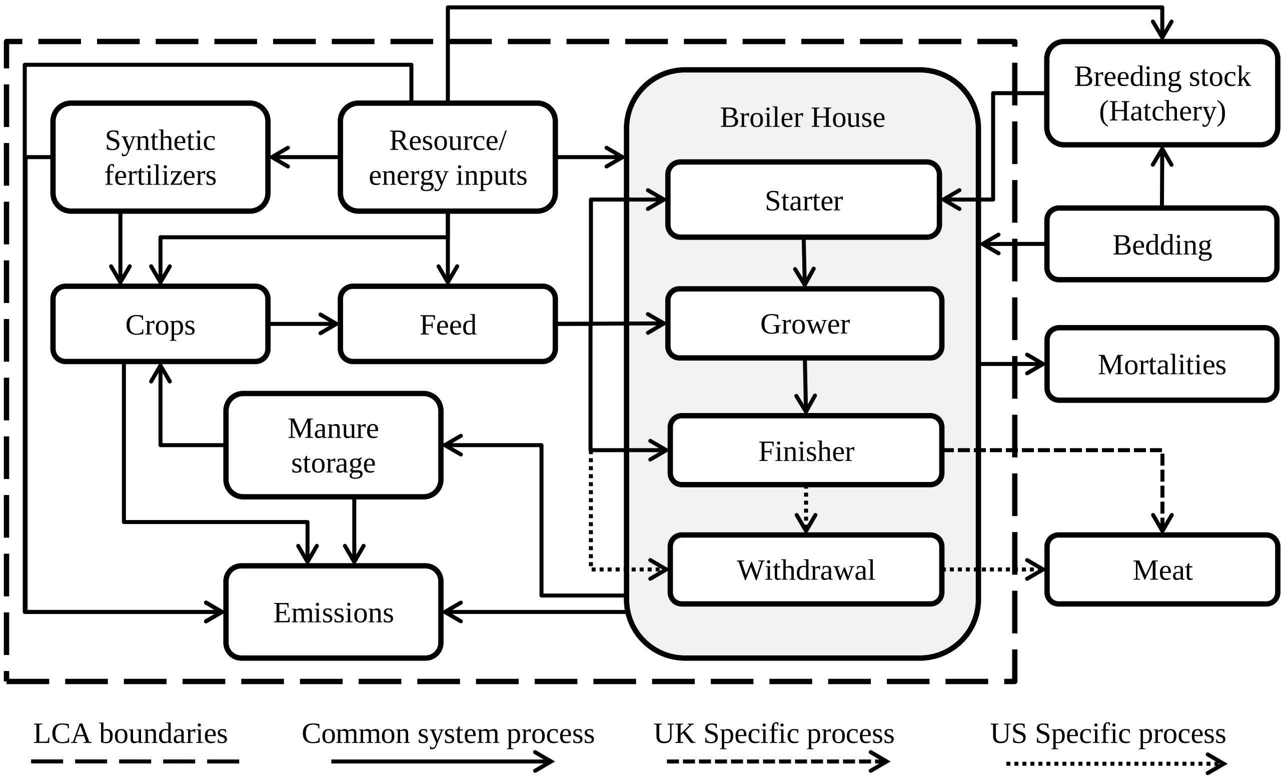

Figure 1: The structure and main components of the broiler production systems as considered by the Life Cycle Assessment (LCA) model; the inputs, outputs and system boundary (dashed line) of the model are shown for both the UK and US poultry production systems.

The main compartment of material flow in the life cycle inventory consisted of the production of feed ingredients. The ingredients that were available to be incorporated into the poultry diets in each region, along with the recommended maximum and minimum inclusion rates, were based on input data from literature, national inventory reports, databases (e.g. FAOSTAT, 2015, Defra, 2015, USDA, 2015) and expert knowledge (Aviagen; personal communication). There are differences in the availability and yield of ingredients between the two regions. For instance, wheat yield in the UK is much greater than in the US; on the other hand maize yields are much better in the US than in the UK (see Table S4 in the supplementary material). Other ingredients could be incorporated into the US diets but not into the UK diets due to EU legislation, such as meat and bone meal (Brookes, 2001). Some high protein crop ingredients were available to be incorporated into the UK diets to stand in for animal co-products, such as field peas and to a lesser extent, sunflower meal. An inventory of feed ingredients specific to each region was then compiled in Simapro (version 8.0.3.14) and this software was used to conduct the LCA calculations. Resource inputs to fertilizer production and the emissions that arise as a result of their application to fields, as well as the energy inputs to processing and transport of ingredients, all contribute to the impacts associated with feed production and all were accounted for within the boundaries of the model. The impact values of the production of ingredients for the UK and US systems can be found in Tables 1 and 2 respectively (section 2.4).

It was expected that the broiler housing conditions were maintained in such a way as to provide the birds with the optimum growing conditions for their genotype in each region. The energy and resource inputs into the hatchery and broiler house were included within the scope of the model and were obtained from literature (Leinonen et al., 2012, Dunkley et al., 2015); however the feed requirements of the breeding stock were not including within the boundaries of the LCA. The feed formulation was not sensitive to the inputs into the hatchery as it was unchanged between feed formulations. The requirement of bedding (wood shavings) per bird was typical of an average conventional UK system (Leinonen et al., 2012) and kept the same between regions and scenarios. The impacts associated with sourcing the bedding material were included; when combined with manure, this is collectively referred to as litter and is a source of emissions associated with poultry production both during and after housing. Average broiler mortality was 3.5% in the UK and 4.5% in the US, with a disproportionately high mortality rate in the starter phase (approx. 2%), and a relatively low mortality rate during the grower phase (approx. 0.7%) and finisher phase (approx. 0.8% and 1.2% in the UK and US respectively); further, the US poultry systems experienced an additional 0.6% mortality in the withdrawal phase (Xin et al., 1994, Leinonen et al., 2012, The Poultry Site, 2004). The US poultry system experienced more mortality only due to a longer growth cycle. Mortality resulted in the consumption of feed with no contribution towards the functional unit, however any emissions associated with the disposal of dead birds was not attributed to the systems.

2.2. Manure model

The nitrogen (N), phosphorous (P) and potassium (K) content of the poultry manure was calculated using the mass balance principle; the nutrients retained in the broiler's body (McGahan and Tucker, 2003) were subtracted from the total N, P and K supplied by the diet. A value for each impact category was calculated based on the excretion of one kg of each nutrient and this was utilised in the diet formulation tool. The manure model estimated the emissions of ammonia (NH_3), nitrous oxide (N_2O) and nitrogen oxides (NO_x), nitrate (NO_x) and phosphate (PO_4) that occurred during housing, storage, and application to field. The emissions were accounted for in accordance with the methodologies for calculating emissions from managed soils, livestock and manure management and storage, outlined by the IPCC (2006). The total N_2O was assumed to equate to the same value as NO_x, as was assumed in the Velthof et al. (2012) model.

After removal from the broiler house, manure was stored in field heaps for 6 months prior to spreading on the land; in the UK and US it is typical that manure is applied to a field once or twice per year so covered storage is recommended (Gates et al., 2008, Defra, 2011). Due to the limited emissions data available for the US and to keep the methodologies consistent, the emissions arising from the US litter at the housing and storage stages was assumed to be equitable to those arising from the UK system as a percentage of the nutrients released in the manure. The housing and storage stages of the US manure model were adapted to reflect regional litter management practices and emission factors as part of the sensitivity analysis. For a full list of the emission factors and their sources used in the manure model refer to the supplementary material (Table S3).

Broadcast field spreading, followed by incorporation through tillage (within 24 hours), was assumed for both regions due to manure management statistics and local codes of practice (USDA, 2009, Defra, 2014a). Only 1.6% of K was lost before it reached the field whilst the loss of P before it reached the field was negligible (Defra, 2011). Phosphate emissions at the field ranged between 2 and 15%, as was reported by Struijs et al. (2011). N_2O and NO_3 emissions at the field were calculated based on IPCC (2006) emission factors which were adapted to the climatic conditions of each region. The nutrients incorporated into the soil replaced N, P and K, which would have otherwise been delivered in the form of synthetic fertilizers, by 70%, 80% and 100% respectively (Williams et al., 2006, Ritz and Merka, 2013): predominantly in the form of ammonium nitrate, potassium chloride, potassium sulphate and di-ammonium phosphate. Offsetting the need to apply as much synthetic fertilizer can be credited to the poultry production system, as is commonly done in livestock LCAs (e.g. Williams et al., 2006, Leinonen et al., 2012, Mackenzie et al., 2015).

2.3. Impact assessment

The metrics used to quantify the environmental impacts of the different diet formulations followed the recommendations made by LEAP (2015a, 2015b): GWP, EP, AP, ALU and NREU. GWP was quantified as CO_2 equivalent (CO_2 eq.) with a 100 year timescale. Under these conditions, 1 kg of CH_4 and N_2O emitted were equivalent to 25 and 298 kg of CO_2 respectively (IPCC, 2006). The CO_2 eq. released due to land transformation was included within the GWP methodology following the PAS2050:2012-1 methodology detailed in BSI (2012). The EP impacts were separated into marine EP (MEP) for N-based emissions and fresh water EP (FWEP) for P emissions, using the ReCiPe midpoint method (Goedkoop et al., 2008), which were taken into account when the Agri-footprint database used in this model was developed. This methodology characterized the emissions of SO_2 eq. to air in terms of terrestrial AP (TAP). The non-renewable energy use was calculated in accordance with the IMPACT 2002+ methodology (Jolliet et al., 2003).

2.4. Diet formulation rules

All diets were formulated for a fixed set of minimum nutritional requirements for the different phases modelled (Aviagen, 2014a, 2014c). Since these requirements were met in every diet formulated, it was assumed that growth rate per kg of feed was unaffected. Therefore 454.5 birds and 1595.3 kg of feed were required in the UK and 357.1 birds and 1742.3 kg of feed were required in the US to achieve the functional unit (discounting birds and the feed they consumed, which die before reaching slaughter). Nutrient contents for all ingredients available to poultry diets in each region were taken from Premier

Nutrition (2014) and placed into a diet formulation matrix. The most recent prices of region specific ingredient were obtained from grey literature; for the UK (Table 1), most prices were obtained from the Department for Environment (2016) and for the US (Table 2) most prices were obtained from the United States Department of Agriculture (2016). Information on the prices of oils and more specialist ingredients, which were not reported in national agricultural statistics documents, were obtained from ingredient specific sources (IndexMundi, 2016, Agriculture and Horticulture Development Board, 2016, University of Missouri, 2016). The prices of synthetic acids were obtained directly from industry (Evonik; personal communication). Maximum and minimum inclusion limits were placed on the individual ingredients in the diets with the aid of input from industry (Aviagen; personal communication), so that issues of palatability, inhibition of digestibility or variability in specific ingredients did not adversely affect bird performance (Table S6 and S7 in supplementary material). Using the linear programming tool “Solver” (Mason, 2012), least cost broiler diets were formulated for each growth phase in each region that met the broiler energy and nutrient specifications. The minimum crude protein requirement of each breed, as was defined by industry for each phase, was at least met by each diet; it was allowed to fluctuate above this level which enabled for more or less synthetic amino acid inclusion. Ingredient background data was derived mainly from the Agri-footprint (2014) database within Simapro, which in turn is a derivative of the Feedprint project, in order to calculate the average GWP, FWEP, MEP, TAP, NREU and ALU per kg of each ingredient (Agri-footprint, 2016). These values were added to the list of ingredient properties in the matrix of the diet formulation tool (Tables 1 and 2). Fossil fuel inputs to fertilizer production, emissions resulting from the spreading of fertilizers, energy inputs to processing (drying, grinding etc.) and transport, all heavily contributed to the impacts associated with the feed production. Where system separation was not possible, coproduct allocation within the feed supply chain was conducted using economic allocation, in accordance with the method recommended by the FAO (2015) and used by Mackenzie et al. (2016b).

A sum of the environmental impact of feed ingredient production and litter management (section 2.2.) provided the total environmental impact associated with the diet formulation for each impact category tested. Therefore, by using linear programming, seven diets were formulated for each region including the least cost diets; the mathematical formulation of the linear optimisation procedure is detailed in the supplementary material. The diets formulated to minimise each impact category individually were as follows: least GWP, least FWEP, least MEP, least TAP, least NREU and least ALU. Each diet was compared to the least cost diet, which would most closely represent a contemporary commercial broiler feed composition. All diets formulated for environmental impact objectives axiomatically resulted in an increased cost as compared to the least cost diet formulation; therefore, in order to formulate economically viable diets, each least environmental impact diet was subject to a 30% maximum cost increase in comparison to the least cost diet (Mackenzie et al., 2016a).

Table 1: Environmental impact values and prices for 1kg of each ingredient produced for use in UK broiler feed. The impact categories tested were global warming potential (GWP; kg CO_2 eq.), freshwater eutrophication potential (FWEP; kg P eq.), marine eutrophication potential (MEP; kg N eq.), terrestrial acidification potential (TAP; kg SO_2 eq.), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; m^2).

UK diet Ingredients	GWP	FWEP	MEP	TAP	NREU	ALU	Price (£/tonne)
Wheat	0.290	0.000109	0.00916	0.01440	2.60	1.05	110
Maize (Corn)	0.450	0.000202	0.00783	0.01520	5.78	1.13	145
Maize gluten meal	0.760	0.000207	0.00754	0.01690	10.8	1.17	510
Rapeseed (Canola) Whole	1.03	0.000497	0.02830	0.04210	6.23	3.31	255
Rapeseed meal	0.450	0.000204	0.01160	0.01730	2.90	1.35	165
Barley	0.300	0.000189	0.00863	0.01480	2.77	1.36	100
Sunflower meal	0.920	0.000670	0.01220	0.02124	6.50	4.30	155
Soybeans	3.88	0.000492	0.01060	0.02550	5.93	3.94	380
Soy meal	3.05	0.000387	0.00833	0.01990	4.62	3.11	280
Field peas	0.400	0.000857	0.00920	0.01860	3.23	5.51	120
Oats	0.300	0.000283	0.01000	0.01890	2.68	1.23	95
Vegetable Oil Blend[1]	5.31	0.002360	0.04180	0.07800	24.7	12.1	575
Soy Oil	8.78	0.001100	0.02370	0.05710	14.6	8.85	600

Limestone	0.160	0.000043	0.00003	0.00077	58.0	0.010	50
Mono Calcium Phosphate	1.47	0.000005	0.00013	0.02300	21.5	0.00	470
NaHCO3	0.230	0.000109	0.00015	0.00283	3.06	0.00	300
Salt	0.150	0.000001	0.00002	0.00105	1.92	0.00	120
Lysine HCl	3.67	0.002330	0.18500	0.35000	23.8	5.75	940
DL-Methionine	1.89	0.000262	0.00134	0.00803	54.7	0.020	2800
L-Threonine	5.22	0.000962	0.00489	0.02430	90.9	0.74	1240
Valine	7.35	0.004670	0.37000	0.70000	47.5	11.5	5200
Fishmeal	0.950	0.000296	0.00087	0.00163	20.0	0.00	1050
Wheat middlings	0.180	0.000057	0.00480	0.00755	1.68	0.550	140
Wheat Bran	0.180	0.000057	0.00481	0.00756	1.68	0.550	130
Brewers Grains	0.790	0.000344	0.01330	0.02230	10.6	1.38	55
Premix	1.30	0.023000	0.04000	0.07500	28.0	0.00	2000
Enzyme (NSP[2]/2*Phytase)	2.28	0.002500	0.00370	0.00700	30.0	0.00	7000

[1]50:50 ratio blend of Sunflower and Palm oil

Table 2: Environmental impact values and prices for 1kg of each ingredient produced for US broiler feed. The impact categories tested were global warming potential (GWP; kg CO_2 eq.), freshwater eutrophication potential (FWEP; kg P eq.), marine eutrophication potential (MEP; kg N eq.), terrestrial acidification potential (TAP; kg SO_2 eq.), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; m^2).

US diet ingredients	GWP	FWEP	MEP	TAP	NREU	ALU	Price ($/tonne)
Wheat	0.480	0.000124	0.00923	0.01560	5.29	1.90	190
Maize (Corn)	0.360	0.000184	0.00489	0.01140	4.91	1.09	130
Maize Gluten meal	0.720	0.000195	0.00519	0.01520	10.3	1.14	465
Rapeseed (Canola) Whole	1.21	0.002050	0.03980	0.05550	11.5	6.68	585
Rapeseed meal	0.530	0.000835	0.01630	0.02310	5.27	2.73	540
Barley	0.300	0.000192	0.00862	0.01480	2.74	1.36	265
Soybeans	0.510	0.000354	0.00955	0.02230	5.16	3.70	400
Soy meal	0.400	0.000279	0.00753	0.01760	4.08	2.92	335
Vegetable Oil Blend[1]	3.50	0.001080	0.02180	0.04880	13.2	5.26	745
Soy Oil	1.22	0.000794	0.02140	0.05080	13.1	8.31	825
Limestone	0.160	0.000043	0.00003	0.00077	58.0	0.010	50
Mono Calcium Phosphate	1.47	0.000005	0.00013	0.02300	21.5	0.00	685
NaHCO3	0.230	0.000109	0.00015	0.00283	3.06	0.00	440
Salt	0.150	0.000001	0.00002	0.00105	1.92	0.00	175
Lysine HCl	3.67	0.002330	0.18500	0.35000	23.8	5.75	1370
DL-Methionine	1.89	0.000262	0.00134	0.00803	54.7	0.020	4090
L-Threonine	5.22	0.000962	0.00489	0.02430	90.9	0.740	1810

Valine	7.35	0.004670	0.37000	0.70000	47.5	11.5	7590
Fishmeal	0.950	0.000296	0.00087	0.00163	20.0	0.00	1535
Meat and Bone meal	0.650	0.000092	0.00308	0.00308	6.46	0.410	275
Poultry Offal	0.340	0.000055	0.00181	0.00752	1.42	0.320	455
DDGS (Corn)	0.700	0.000223	0.00256	0.00600	8.22	0.540	190
Brewers grains	0.640	0.000484	0.00823	0.01280	10.2	1.38	140
Premix	1.30	0.023000	0.04000	0.07500	28.0	0.00	2920
Enzyme (NSP[2]/2*Phytase)	2.28	0.002500	0.00370	0.00700	30.0	0.00	10220

[1]50:50 ratio blend of Soy and Palm oil

2.5. Sensitivity Analysis

A sensitivity analysis was performed on the model based on the least cost diet formulations for both the UK and US; hence the sensitivity analysis identified the parameters that have the most influence on the model outputs (section 2.5). The sensitivity analysis was conducted on all input parameters to the foreground LCA model on an individual basis at the upper/lower 95% confidence bounds of their distributions, as is appropriate for models which contain linear relationships (Mackenzie et al., 2015). The distributions of the parameters were derived from appropriate sources, such as published industry benchmark data for flock performance characteristics and crop yields, as well as peer reviewed studies and IPCC guidelines on emission factors from manure management (see Table S4 and S5 in the supplementary material for a full list of the parameters tested and the sources used to fit their means and distributions). If the upper or lower bounds for any parameter resulted in ≥5% change in any impact value in comparison to the mean result of the LCA for the least cost diets then this was reported as a sensitive input to the LCA model (Mackenzie et al., 2016a).

In the first instance, emissions in the manure model were accounted for in accordance with the IPCC (2006) methodologies using the same emissions factors for the housing and storage stages in both regions; in reality, however, litter management practices vary between the two regions. Since the base model assumed UK storage and housing emission values as a percentage of the nutrients released by the birds in both regions, the manure model was adapted to reflect emission values recorded in US poultry housing and manure storage (e.g. Coufal et al., 2006, Moore et al., 2011) to assess the sensitivity of the US least cost diet to the potential difference in litter management practices and emissions between the regions. Where environmental impact categories were sensitive to this change (i.e. ≥5% compared to the base model), the corresponding least impact diets were reformulated using the US specific manure model.

2.6. Uncertainty

In order to make it possible to evaluate differences between the least cost diet and the diets formulated for environmental impact objectives a Monte Carlo approach (Figure 2) was applied to the model to quantify the potential uncertainties in the study (e.g. measurement errors, variation in production data due to differences in crop yield, feed intake, bird mortality etc.). Uncertainties in LCA calculations can be classified as either system "α" or shared calculation "β" uncertainties (Wiltshire et al. 2009): α uncertainties are those considered to vary between systems, while β uncertainties are the same for both systems and in some earlier studies they have simply been ignored (e.g. Leinonen et al., 2012). The comparisons made in the LCA model were between different diets tested in the same regional production scenario (for US and UK systems respectively), as such most of the uncertainty contained in this LCA model was shared between the comparisons and classed as β uncertainty (Leinonen et al., 2012, Mackenzie et al., 2016a). In order to assess whether dietary scenarios were significantly different from each other in terms of their environmental impacts once they were applied to the poultry production system within each region, the LCA model was run in parallel 1000 times and, during each run, a value of each input variable was randomly selected from a predetermined distribution for said variable; the method is described comprehensively in Mackenzie et al. (2015). The price uncertainty of commodities, such as the feed ingredients, was beyond the scope of this study. A full list of mean values, distributions and sources for the input parameters to the LCA model can be found in Table S4 and S5 in the supplementary material. Environmental impact results were reported as significantly different where one diet had a greater impact than the other in more than 95% of the parallel simulations of the LCA model ($p<0.05$).

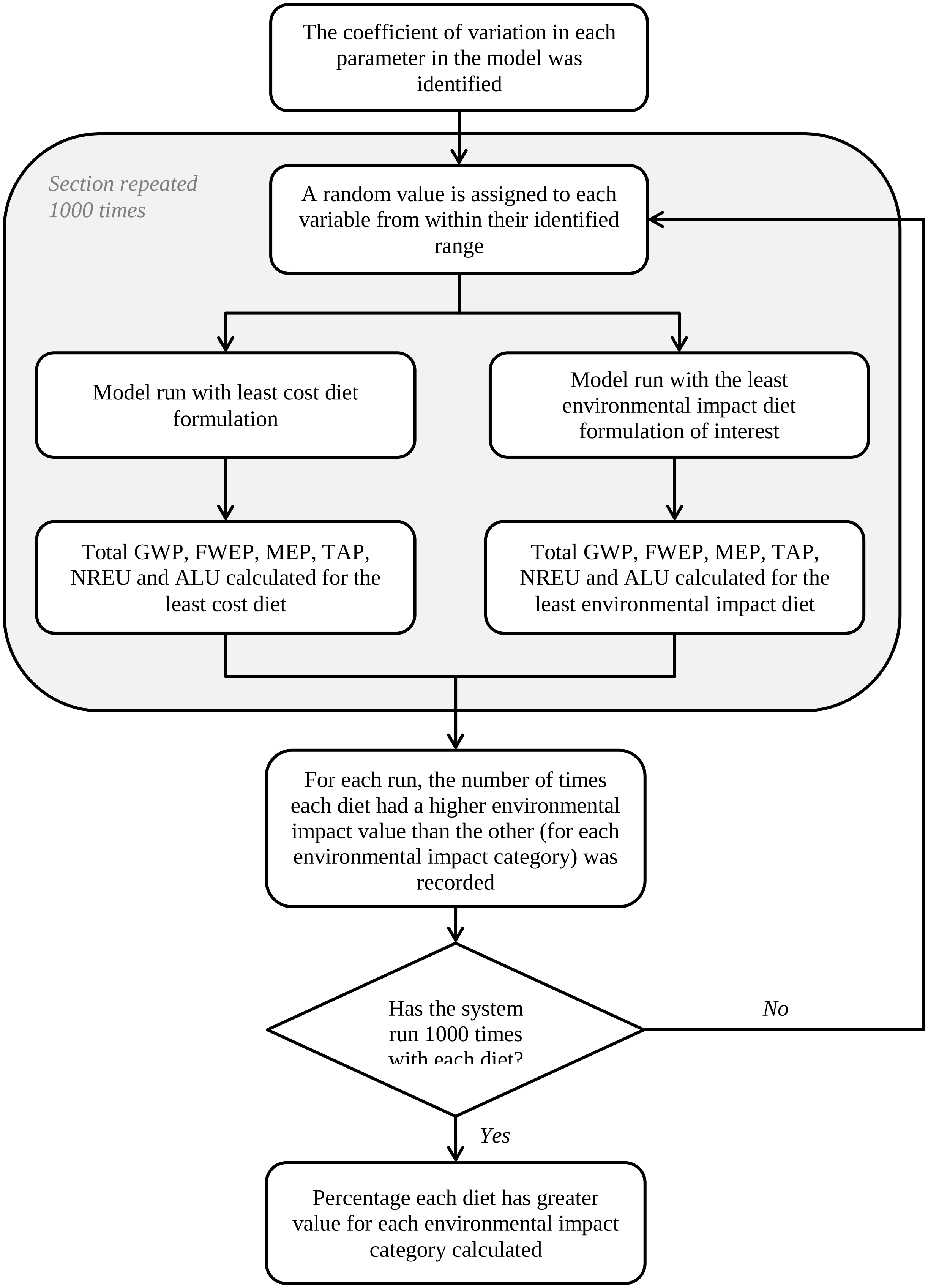
The coefficient of variation in each parameter in the model was identified
Section repeated 1000 times
A random value is assigned to each variable from within their identified range
Model run with least cost diet formulation
Model run with the least environmental impact diet formulation of interest
Total GWP, FWEP, MEP, TAP, NREU and ALU calculated for the least cost diet
Total GWP, FWEP, MEP, TAP, NREU and ALU calculated for the least environmental impact diet
For each run, the number of times each diet had a higher environmental impact value than the other (for each environmental impact category) was recorded
Has the system run 1000 times with each diet?
No
Yes
Percentage each diet has greater value for each environmental impact category calculated

Figure 2: Flow diagram to illustrate how the Monte Carlo simulations were run. The impact categories tested were global warming potential (GWP; kg CO_2 eq.), freshwater eutrophication potential (FWEP; kg P eq.), marine eutrophication potential (MEP; kg N eq.), terrestrial acidification potential (TAP; kg SO_2 eq.), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; m^2).

3. Results

3.1. Least cost diet formulation and sensitivity analysis

In the UK a standard least cost diet, across all three stages, was composed of 483 g/kg wheat, 66.8 g/kg rapeseed, 241 g/kg soymeal and 124 g/kg field peas, plus oil and specialist ingredients. The production of the functional unit on the least cost diet had a GWP, FWEP, MEP, TAP, NREU and ALU impact value of 3060 kg CO_2 eq., 0.6657 kg P eq., 27.38 kg N eq., 69.61 kg SO_2 eq., 16.63 GJ and 4675 m^2 respectively (section 3.2). The cost of feed with a least cost formulation was £0.21 per kg in the UK. In the US, a standard least cost diet was composed of 611 g/kg maize and 208 g/kg soymeal plus oil, animal coproducts and additives (section 3.3). The production of the functional unit on the least cost diet had a GWP, FWEP, MEP, TAP, NREU and ALU impact value of 917.7 kg CO_2 eq., 0.4154 kg P eq., 20.66 kg N eq., 63.16 kg SO_2 eq., 12.24 GJ and 2775 m^2 respectively. The cost of feed with a least cost formulation was $0.24 per kg.

Tables 3 and 4 list the variables which caused ≥5% sensitivity for any of the impact categories tested in the UK and US respectively. In the UK, every impact category was sensitive to the live weight achieved for a given feed intake and feed intake for a given live weight achieved, otherwise known as feed conversion ratio (Table 3). Every impact category was affected significantly by differences in the age at which the broilers were taken to slaughter in the UK, whilst no impact category was sensitive to changes in mortality or feed spillage. Variation in soybean yield caused sensitivity in GWP and ALU in the UK, whilst FWEP and ALU were sensitive to field pea yield. The results for TAP were sensitive to variation in NH_3 emissions released at the UK housing and storage stages; the TAP was also sensitive to the retention of N in the birds' bodies and the minimum replacement rate of N that would have been otherwise delivered via the spreading of synthetic fertilizers. FWEP was sensitive to the variation in the replacement rate of P that would have been otherwise delivered via the spreading of synthetic fertilizers in the UK. NREU was sensitive to gas consumption at the UK facilities. MEP and FWEP were highly sensitive to assumptions regarding any net difference in leaching of NO_3 and PO_4 respectively, caused by applying manure to land in place of inorganic fertilizer in the UK.

Table 3: Variables in the UK model which were sensitive in at least one impact category. The effect of increasing each variable to the maximum (upper 95% confidence bounds of their distribution) and minimum (lower 95% confidence bounds of their distributions) value in its range on each environmental impact category is shown. Results are presented as the percentage increase (+) or decrease (-) from the median. The impact categories tested were global warming potential (GWP; kg CO_2 eq.), freshwater eutrophication potential (FWEP; kg P eq.), marine eutrophication potential (MEP; kg N eq.), terrestrial acidification potential (TAP; kg SO_2 eq.), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; m^2). For the full sensitivity analysis refer to the supplementary material (Table S8).

Environmental impact category	GWP		FWEP		MEP		TAP		NREU		ALU	
Variable	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Live weight at slaughter	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70
Feed intake	+8.25	-8.25	+9.73	-9.73	+9.74	-9.74	+9.63	-9.63	+4.97	-4.97	+9.73	-9.73
Age	-14.8	-19.0	-16.1	-23.3	-17.3	-17.5	-18.2	-13.0	-12.1	-9.64	-15.8	-24.7
Soybean yield	-6.37	+6.37	-	-	-	-	-	-	-	-	-5.22	+5.22
Field pea yield	-	-	-5.85	+5.85	-	-	-	-	-	-	-5.36	+5.36
NH_3 lost at housing	-	-	-	-	-	-	-	-5.93	-	-	-	-
NH_3 lost at storage	-	-	-	-	-	-	-	-8.28	-	-	-	-
Gas consumption	-	-	-	-	-	-	-	-	+11.8	-11.8	-	-
N retention	-	-	-	-	-	-	-5.57	+5.57	-	-	-	-
N replacement rate	-	-	-	-	-	-	-	+9.89	-	-	-	-
P replacement rate	-	-	-6.77	+6.77	-	-	-	-	-	-	-	-
NO_3 emissions	-	-	-	-	-	-7.69	-	-	-	-	-	-
PO_4 emissions	-	-	+66.3	-19.9	-	-	-	-	-	-	-	-

In the US system the GWP, FWEP, NREU and ALU were sensitive to low slaughter age compared to the mean slaughter age of 44 day (Table 4). The MEP and the TAP were sensitive to slaughtering broilers at a high age compared to mean slaughter age. No impact category was sensitive to potential differences in mortality or feed spillage. Every impact category was sensitive to the birds' feed conversion ratio. The FWEP was sensitive to high and low US maize yield. The results for TAP were sensitive to variation in NH_3 emissions at every stage of the manure model. TAP was also sensitive to the minimum replacement rate of N. FWEP was sensitive to the variation in the replacement rate of P. MEP and FWEP were highly sensitive to assumptions regarding any net difference in leaching of NO_3 and PO_4 respectively, caused by applying manure to land in place of inorganic fertilizer. There was no sensitivity in any impact category for P and K retention in the US broilers' bodies; however MEP and TAP were sensitive to variation in N retention.

Table 4: Variables in the US model which were sensitive in at least one impact category. The effect of increasing each variable to the maximum (upper 95% confidence bounds of their distribution) and minimum (lower 95% confidence bounds of their distributions) value in its range on each environmental impact category is shown. Results are presented as the percentage increase (+) or decrease (-) from the median. The impact categories tested were global warming potential (GWP; kg CO_2 eq.), freshwater eutrophication potential (FWEP; kg P eq.), marine eutrophication potential (MEP; kg N eq.), terrestrial acidification potential (TAP; kg SO_2 eq.), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; m^2). For the full sensitivity analysis refer to the supplementary material (Table S9).

Environmental impact category	GWP		FWEP		MEP		TAP		NREU		ALU	
Variable	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Live weight at slaughter	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70	-7.41	+8.70
Feed intake	+8.11	-8.11	+9.71	-9.71	+9.75	-9.75	+9.70	-9.70	+7.64	-7.64	+9.71	-9.71
Age	-	-8.99	-	-8.30	-7.22	-	-8.19	-	-	-8.24	-	-8.98
Maize yield	-	-	-5.58	+5.58	-	-	-	-	-	-	-	-
Soybean yield	-	-	-	-	-	-	-	-	-	-	-8.15	+8.15
NH_3 lost at	-	-	-	-	-	-	+10.0	-8.25	-	-	-	-

housing												
NH_3 lost at storage	-	-	-	-	-	-	-	-12.1	-	-	-	-
NH_3 lost at field	-	-	-	-	-	-	+7.33	-7.33	-	-	-	-
N retention	-	-	-	-	-5.14	+5.14	-6.05	+6.05	-	-	-	-
N replacement rate	-	-	-	-	-	-	-	+11.7	-	-	-	-
P replacement rate	-	-	-16.0	+16.0	-	-	-	-	-	-	-	-
NO_3 emissions	-	-	-	-	-	-14.2	-	-	-	-	-	-
PO_4 emissions	-	-	+70.8	-49.6	-	-	-	-	-	-	-	-

Finally, adapting the manure model so that the emissions values from the US system were distinctly different than those from the UK, reflecting measurements taken from US production systems at both the housing and storage stages (see Table S3 in the supplementary material), led to a 39.2% significant increase in TAP in the US least cost diet scenario compared to the US least cost scenario where the emissions at housing and storage were equitable with those in the UK. All other impact categories were not sensitive to this adaptation.

3.2. Least environmental impact diet formulations - UK

When compared to the least cost diet, soymeal was reduced in the least GWP diet in favour of maize gluten meal, rapeseed meal and sunflower meal, which were incorporated at inclusions of 48.3, 34.2 and 88.6 g/kg respectively; wheat was also reduced, when compared to the least cost diet, at 453 g/kg, but whole rapeseed remained the same (Table 5). In the least FWEP diet, wheat inclusion was increased, but rapeseed was removed completely. In the least MEP and TAP diets maize usurped wheat as the primary energy ingredient (577 and 630 g/kg respectively) and had an increased soy oil content relative to the least cost and least GWP diets. The NREU diet had a greater inclusion of wheat and soymeal when compared to the least cost diet. Like the least MEP and TAP diets, the least ALU diet was primarily maize based, but also contained 66.3 g/kg of whole rapeseed.

Table 5: Percentage inclusion of each ingredient in each diet formulated for the UK poultry systems. The diets were formulated for least global warming potential (GWP; kg CO_2 eq.), least freshwater eutrophication potential (FWEP; kg P eq.), least marine eutrophication potential (MEP; kg N eq.), least

terrestrial acidification potential (TAP; kg SO_2 eq.), least non-renewable energy use (NREU; MJ) and least agricultural land use (ALU; m^2).

	Diet						
Ingredient	Least Cost	Least GWP	Least FWEP	Least MEP	Least TAP	Least NREU	Least ALU
Wheat	48.3	45.3	63.3	0.00	0.00	55.0	0.00
Maize (Corn)	0.00	0.00	0.00	57.8	63.0	0.00	58.9
Maize gluten meal	0.33	4.83	4.83	0.00	0.00	0.18	4.83
Rapeseed (canola) Whole	6.68	6.68	0.00	0.00	0.00	6.68	6.63
Rapeseed meal	0.00	3.42	0.00	0.00	0.00	0.00	0.00
Barley	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sunflower meal	0.00	8.86	0.00	0.00	0.00	0.00	0.00
Soybeans	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Soy meal	24.1	5.94	20.1	26.8	26.2	29.9	20.8
Field peas	12.4	12.4	0.00	0.00	0.00	0.00	0.00
Oats	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vegetable Oil[1]	0.00	4.58	0.00	0.00	0.00	0.00	0.00
Soy Oil	4.18	0.16	3.69	4.71	3.02	4.17	0.53
Limestone	1.15	1.00	1.00	1.75	1.00	1.00	1.00
Mono Calcium Phosphate	1.29	0.71	0.78	1.24	0.85	1.57	0.86
NaHCO3	0.00	0.00	0.00	0.13	0.00	0.00	0.00
Salt	0.37	0.27	0.28	1.85	0.28	0.37	0.27
Lysine HCl	0.17	0.32	0.24	0.14	0.14	0.15	0.20
DL-Methionine	0.28	0.18	0.50	0.26	0.25	0.24	0.50
L-Threonine	0.09	0.06	0.04	0.05	0.05	0.06	0.21
Valine	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Fishmeal	0.42	5.00	5.00	5.00	5.00	0.42	5.00
Brewers Grains	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wheat middlings	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wheat Bran	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Premix	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Enzyme (NSP2/ 2*Phytase)	0.03	0.03	0.03	0.03	0.03	0.03	0.03

[1]50:50 ratio blend of Sunflower and Palm oil

All least environmental impact diets had increased costs of between 16 and 30% when compared to the least cost diet, except for the NREU diet which had an increased cost of just under 4% (Figure 3). The least MEP and ALU diets were 29% and 30% more expensive than the least cost diet, at the top end of the upper economic limit applied to the diet formulation tool. The least GWP diet decreased the GWP by

37%, but increased NREU by 31% and TAP by 8.2%. The Least FWEP diet decreased the values of all impact categories, when compared to the least cost diet, with the exception of TAP which increased by 0.07% and the NREU, which was not significantly different. The least MEP and TAP diets showed similar trends in the reduction of environmental impacts; however every impact category except MEP was lower in the least TAP diet. The least NREU diet was the only diet which had a significantly lower NREU value than the least cost diet. The least ALU diet reduced significantly the GWP, FWEP and MEP compared to the least cost diet, but resulted in a small significant increase in TAP (0.62%) and a 53.2% significant increase in NREU.

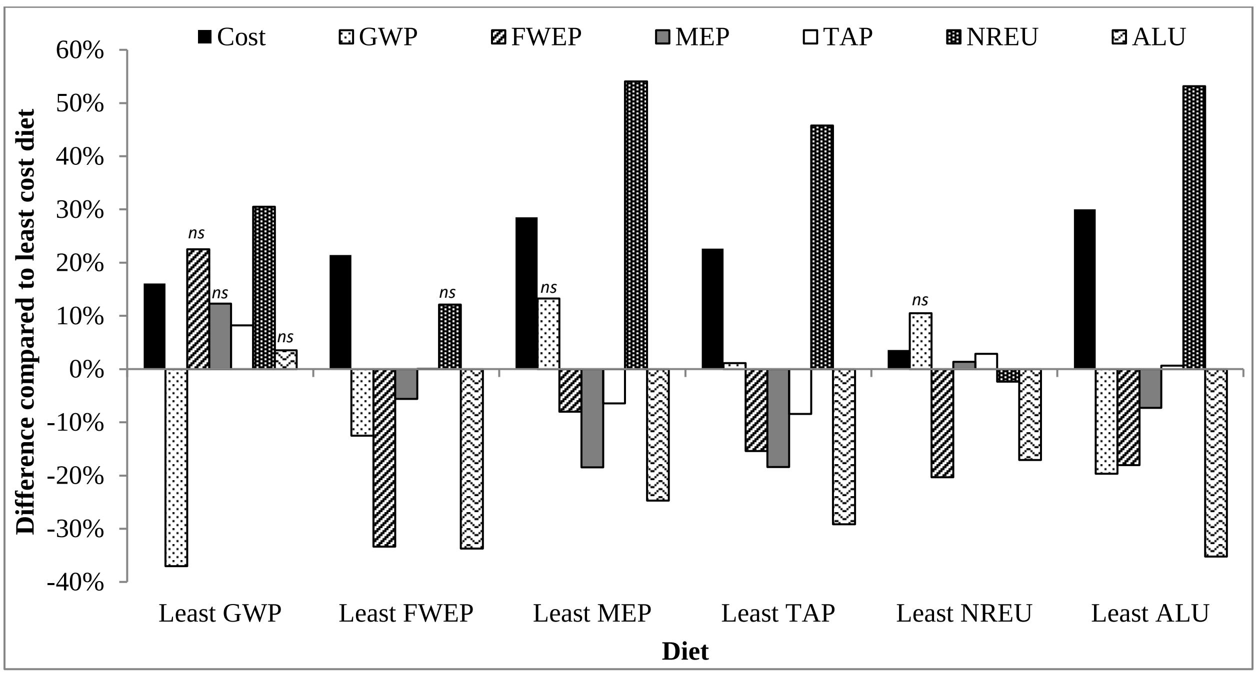

Figure 3: Environmental impacts of different UK broiler diets, each formulated to reduce a specific environmental impact category, as compared to a least cost formulation baseline. The price is also included for each diet (£).The impact categories tested were global warming potential (GWP; kg CO_2 eq.), freshwater eutrophication potential (FWEP; kg P eq.), marine eutrophication potential (MEP; kg N eq.), terrestrial acidification potential (TAP; kg SO_2 eq.), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; m^2). All impact category values were significantly different (p <0.05) from

their corresponding value produced by the functional unit on the least cost diet unless otherwise stated as being nonsignificant (*ns*).

3.3. Least environmental impact diet formulations - US

In contrast to the UK diets, the US diets consisted of a higher percentage of soymeal in the starter phase, and lower percentage inclusions in the later phases (Table 6). In the least GWP diet maize incorporation was reduced dramatically (307 g/kg) when compared to the least cost baseline and instead barley was included as an additional energy source (262 g/kg). Ingredients derived from soybeans increased, which was the opposite of what happened in the UK least GWP diet. In the least FWEP diet wheat usurped maize as the primary energy ingredient and was included at a rate of 664 g/kg. The incorporation of maize and fishmeal was high in the least MEP and TAP diets when compared to other diet formulations. The least NREU incorporated 277 g/kg of maize and 262 g/kg of barley, much like the least GWP diet, but contained more soybeans (106 g/kg) and slightly less soymeal (228 g/kg) than that diet. The least ALU contained the least soybeans and their derivatives compared to all other US diet formulations and the highest incorporation of specialist ingredients.

Table 6: Percentage inclusion of each ingredient in each diet formulated for the US poultry systems. The diets were formulated for least global warming potential (GWP; kg CO_2 eq.), least freshwater eutrophication potential (FWEP; kg P eq.), least marine eutrophication potential (MEP; kg N eq.), least terrestrial acidification potential (TAP; kg SO_2 eq.), least non-renewable energy use (NREU; MJ) and least agricultural land use (ALU; m^2).

	Diet						
Ingredient	Least Cost	Least GWP	Least FWEP	Least MEP	Least TAP	Least NREU	Least ALU
Wheat	0.00	0.00	66.4	0.00	0.00	0.00	0.00
Maize (Corn)	61.1	30.7	0.00	66.0	63.8	27.7	61.4
Maize gluten meal	2.39	0.00	4.89	0.00	0.00	0.00	4.89
Rapeseed (canola) Whole	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rapeseed meal	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Barley	0.00	26.2	0.00	0.00	0.00	26.2	0.00
Soybeans	0.00	4.37	0.00	0.00	0.00	10.6	0.00
Soy meal	20.8	25.5	14.6	21.1	27.2	22.8	13.8
Vegetable Oil[1]	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Soy Oil	2.19	4.65	2.84	1.95	3.28	4.09	0.91
Limestone	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mono Calcium Phosphate	0.49	0.44	0.12	0.50	1.08	0.43	0.08
NaHCO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salt	0.27	0.29	0.24	0.24	0.33	0.29	0.16
Lysine HCl	0.26	0.03	0.27	0.11	0.15	0.03	0.22
DL-Methionine	0.21	0.22	0.15	0.21	0.25	0.21	0.50
L-Threonine	0.05	0.01	0.05	0.03	0.05	0.01	0.50
Valine	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fishmeal	0.00	0.04	2.85	5.00	2.62	0.00	5.00
Meat and Bone meal	2.65	2.65	2.65	0.00	0.00	2.65	2.65
Poultry Offal	3.65	3.65	3.65	3.65	0.00	3.65	3.65
DDGS (Corn)	4.72	0.00	0.00	0.00	0.00	0.00	5.00
Brewers Grains	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Premix	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Enzyme (NSP2/ 2*Phytase)	0.03	0.03	0.03	0.03	0.03	0.03	0.03

[1]50:50 ratio blend of Soy and Palm oil

All least environmental impact diets had increased costs of between 23% (least TAP) and 30% (Least FWEP) when compared to the least cost diet (Figure 4). The least GWP diet decreased significantly GWP by 6.7% and NREU by 15%, but increased significantly every other impact category. The least FWEP diet caused an 18% decrease in MEP, but increased every other impact category when compared to the least cost diet. The least MEP diet increased the FWEP and NREU compared to the least cost diet. In the least TAP diet only MEP and TAP were significantly reduced compared to the least cost diet. The least NREU had a reduced GWP and NREU when compared to the least cost diet, but increased every other impact category. The Least ALU diet significantly increased every impact category except the FWEP (insignificant change) and ALU (reduced by 18%).

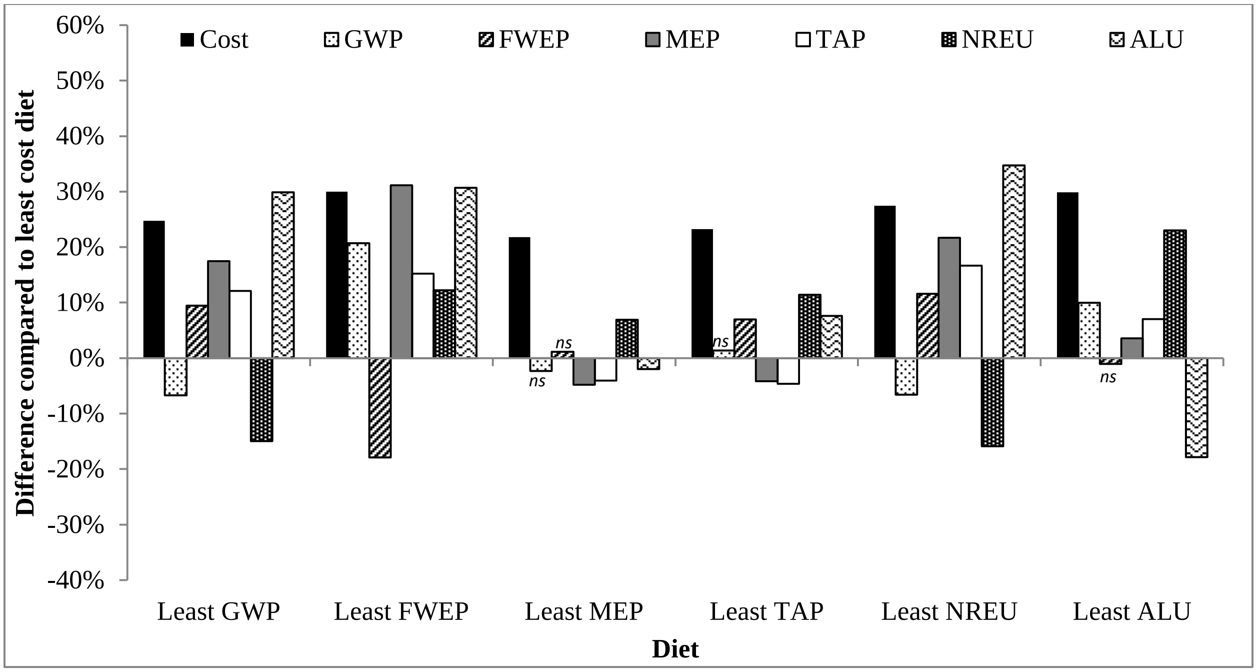

Figure 4: Environmental impacts of different US broiler diets, each formulated to reduce a specific environmental impact category, as compared to a least cost formulation baseline. The price is also included for each diet ($). The impact categories tested were global warming potential (GWP; kg CO_2 eq.), freshwater eutrophication potential (FWEP; kg P eq.), marine eutrophication potential (MEP; kg N eq.), terrestrial acidification potential (TAP; kg SO_2 eq.), non-renewable energy use (NREU; MJ) and agricultural land use (ALU; m^2). All impact category values were significantly different ($p < 0.05$) from their corresponding value produced by the functional unit on the least cost diet unless otherwise stated as being nonsignificant (*ns*).

4. Discussion

In this study the potential for lowering the impact in different environmental impact categories of broiler production in different world regions through diet formulation was explored. Due to legislation, trade agreements and climatic conditions, broilers are fed diets composed of different ingredients in the EU and North America (Van Horne and Bondt, 2013). The inclusion of animal derived co-products in broiler diets, such as meat and bone meal, is a good case in point: this is not allowed in the EU, but is used routinely in North America (Brookes, 2001). It was therefore hypothesised that the potential reduction in specific environmental impact categories, associated with the formulation of the diets, would differ between these two regions. To test this, a whole systems model was developed to formulate broiler diets for environmental impact objectives in the UK and the US as a case in point for EU and North American broiler systems respectively. Least cost diets were formulated for each region to represent the baseline diet which can be considered typical of current broiler production practices; the UK least cost diet was based on wheat and soya and the US least cost diet was based on maize and soya. Although a direct comparison between the two regions was not the intention of this research, the US least cost feed formulation notably had a GWP, FWEP, MEP, TAP and ALU that was 68%, 37%, 46%, 32% and 39% lower per kg than the UK least cost feed diet formulation respectively. From this contrast it might be expected that the UK would show more potential for environmental improvement via feed formulation.

As the LCA model itself contained only linear relationships, a simple analysis that tested parameters on an individual basis was suitable for identifying the inputs to which the environmental impact categories were most sensitive. Based on the inputs of the least cost diets, the sensitivity analysis identified 13 parameters for each region in the model containing uncertainty that affected the results for any impact category greater than ±5%. Of these, 7 and 8 variables were associated with the assumptions made as part of the manure model in the UK and US respectively. In both regions the FWEP was sensitive to P replacement rates of equivalent synthetic fertilizer and the level of PO_4 emissions. MEP was sensitive to nitrate leaching in both regions and bird N retention levels in the US only. TAP was sensitive to NH_3 emissions, N retention in the birds and N replacement rates of equivalent synthetic fertilizer in both regions. The N in the litter could replace synthetic N fertilizer (i.e. ammonium nitrate) by a maximum of 80%. This was to account for the over application to fields that often occurs with poultry litter (Williams et al., 2006). The on-farm energy use in both regions were assigned relatively high levels of variability due to the approximate nature of the energy use values available (Pelletier, 2008, Leinonen et al., 2012, Dunkley et al., 2015, University of Arkansas, 2016). Despite this only the NREU in the UK was sensitive to gas consumption; this is because systems in this region require more gas for maintaining the temperature of the growing facilities for best broiler growth rates. No impact category was sensitive to mortality despite it showing high levels of variability in both regions, this is due to most of the mortality being witnessed in the starter phase, when very little feed had been consumed. In both regions every impact category was sensitive to the assumptions made for FCR.

The methodologies that defined the housing and storage parts of the manure model were kept consistent between the two regions. However, in reality, housing emissions reported in LCAs of US poultry systems (Coufal et al., 2006, Moore et al., 2011) have been consistently higher, and the emissions arising from storage lower, than those reported in the LCAs of UK poultry systems (Demmers et al., 1999, Robertson et al., 2002, Webb and Misselbrook, 2004, Misselbrook et al., 2010). For instance, in the US more NH_3 is released at the housing stage. This could be due to differences in measurement methodologies or in-house litter management practices; in the EU it is standard practice that litter be completely removed after each flock (Compassion in World Farming, 2013). However in the US it has been reported that only one third of contracts state this as a requirement, with about a quarter of growing facilities not being fully cleaned out over the course of a year (MacDonald, 2008). Recycling more litter would result in higher ammonia emissions at the housing stage and result in less N reaching the storage stage, thus less NH_3 volatilization and leach from the storage process. The only environmental impact category that was sensitive to using US emission factors in the manure model was TAP when both methodologies were compared in a least cost diet formation. Reformulating the US least TAP diet using the US specific manure model reduced the inclusion of maize and fish meal, whilst the inclusion of soybean derivatives and synthetic amino acids were increased, when compared to the US least TAP diet formulated using UK housing and storage emission values. The only environmental impact category that was sensitive to this change was the ALU, which was 6% higher when US specific emission factors were applied to the least TAP diet.

Diets were formulated that aimed to reduce one environmental impact category value at a time. The environmental impact values for each diet were calculated holistically using LCA, and were the sum of the total environmental impact of the provision of the feed ingredients and the management of the manure associated with such a diet. In most cases, diets formulated for the US system increased at least three impact categories significantly compared to the least cost diet. The UK on the other hand showed more potential: in most cases at least three impact categories were reduced by targeting one specifically, with the least GWP diet being the only exception in this case. Surprisingly, the least environmental impact diets forced the inclusion of some alternative cereals in both regions that would not be routinely incorporated into least cost formulations. For instance, maize was incorporated into the UK least MEP, TAP and ALU diets. This is because wheat has a greater associated MEP impact value than maize. Although maize has a slightly higher TAP and ALU value than wheat in the UK (Table 1), it was included in the UK least TAP diet as a trade-off for meeting bird nutritional requirements with a lower inclusion of other high TAP and ALU ingredients, such as soy oil.

The UK broiler production system was associated with a much greater GWP than the US system (see Table S10 in the supplementary material). This is because in European livestock systems, including the one modelled in this study, the majority of soya meal used in animal feed is imported from South America (Kebreab et al., 2016). This is associated with recent land use change, such as deforestation, which results in the release of carbon deposits from carbon sinks (Leinonen et al., 2012). In the UK, the GWP associated with broiler feed production was reduced considerably in the least GWP diet by incorporating protein sources which have a lower embedded CO_2 eq. burden associated with them than soya, namely sunflower meal and field peas; furthermore vegetable oil was used instead of soy oil in this diet (Leinonen et al., 2013). In contrast, 100% of the soybeans used in the US system are grown domestically and not associated with land use change. Despite this, the US utilised less soybeans as a protein source, even with maize having a lower protein content, because more protein could be incorporated in the form of animal co-products, banned in poultry feed in the EU since the mid-1990s (Brookes, 2001). GWP was minimised in the US by including barley, which is a cereal associated with a low GWP and NREU but high MEP when compared to maize, and removing DDGS corn, a product with moderately high GWP. Minimising GWP through diet formulation in the US significantly increased

FWEP MEP, TAP and ALU compared to the least cost diet. It is important to acknowledge this when attempting to target GWP only, particularly with regards to the US system which showed high significant increases in other impact categories with only a small reduction in the GWP (Figure 4), as this impact category is often paid the most attention; e.g. in corporate social responsibility reporting or participation in voluntary carbon labelling schemes (Tan et al., 2014). Wheat was used as the primary energy crop in the US least FWEP diet due to its lower associated P emissions compared to maize; this diet had an increased MEP relative to all other diet formulations due to wheat's higher MEP. The diet formulated for least NREU in the US was similar to that formulated for least GWP, in that barley was incorporated and maize was halved compared to the US least cost diet formulation.

Optimization methodologies, such as the one developed here, have been used in the past to reduce feed cost and total phosphorus content in pig systems based on traditional least-cost formulation programs (Jean dit Bailleul et al., 2001, Pomar et al., 2007). The model developed in this study was similar in structure to that developed by Mackenzie et al. (2016a) for Canadian pig systems. Although poultry diet formulation for reduced environmental impacts has recently been attempted for Europe and North America by Kebreab et al. (2016), the novelty of the methodology applied here is that the diets formulated were the output of the model. In their study Kebreab et al. (2016) used LCA to demonstrate that increasing the inclusion of specialty ingredients, such as synthetic amino acids, could reduce the GWP, EP and AP of production compared to a basal diet; the basal diet was formulated for methionine as the first limiting nutrient and contained no synthetic amino acids. In contrast, in the study presented in this paper the least cost diets, to which all the other diets were compared (Figures 3 and 4), were formulated to meet the requirements of the birds using the same rules as every diet formulated to target specific environmental impact categories. Finally, through development of the manure model element of the tool, the methodological challenge of prospectively accounting for the aggregated environmental impacts caused by N, P and K excretion when formulating diets for environmental impact objectives has been overcome. In this way, comparisons of potential least environmentally impact diets to least cost diets in each region are realistic and allow nutritionists and livestock producers alike to easily integrate environmental objectives into current feeding strategies. Although this might seem an obvious point to make, the methodology has not been universally respected.

The least environmental impact diets had an axiomatic increased cost compared to the least cost diets; in most cases this increase was considerable with the exception of NREU in the UK. Two diets had an increased cost of 30%, the upper limit; these were the least ALU diet in the UK and the least FWEP diet in the US. For every other diet formulated for environmental impact objectives the cost limit was not reached; in these cases it was not cost which prevented further reduction in the environmental impact, these were the maximum reductions possible for those impact categories given the systems considered. In several other cases the increase was close to the limit, e.g. the UK least MEP, the US least NREU and the US least ALU. Although the limit was set arbitrarily it would be unrealistic to consider higher increases in diet costs when the business must consider its bottom line (Elkington, 1997, Mackenzie et al., 2016a).

It was not possible in either region to minimise one impact category through diet formulation without increasing at least one other impact category. Although the tool, as described in the methodology of this paper, was not able to formulate a diet that would have reduced environmental impact values for some categories without increasing others, adding post hoc constraints to the tool could do so. For instance, this could be achieved by constraining the maximum TAP increase compared to the UK least cost diet to zero when formulating the UK least FWEP diet. This diet would be 21% more expensive than the least cost formulation, but would reduce the GWP (by 0.13%), FWEP (by 33%), MEP (by 5.6%) and ALU (by 44%) compared to the UK least cost diet. This diet would have an unchanged TAP value and would not significantly affect the NREU value compared to the UK least cost diet. Similarly, if the UK least NREU diet was formulated, whilst the MEP and TAP were constrained so that they may not increase above the levels they were at in the least cost diet, a diet could be formulated that would decrease the FWEP (by 22%), TAP (by 2.2%) and ALU (by 19%) compared to the least cost diet; the GWP would be insignificantly increased. This diet would cost 2.1% more than the least cost diet. By comparison, the potential of such a diet formulation tool, which incorporated post hoc constraints, for environmental impact reduction in the US was relatively limited. This shows that it would be possible to reduce several impact categories without simultaneously increasing others significantly in the UK; however the US has less room for environmental impact improvement. There is currently discussion on how to account for multiple environmental impact categories at the same time (Soares et al., 2006, Finnveden et al., 2009, Mackenzie et al., 2016a). Further development of the diet formulation model, to integrate a multiple criteria decision making approach for formulating broiler diets, would enable multiple environmental impact objectives to be considered to help resolve this issue.

5. Conclusion

Methodologies such as the one applied here, in which a cradle to farm gate LCA model was integrated into a diet formulation tool, can allow nutritionists and livestock producers to integrate environmental objectives into diet formulation, facilitating sustainable feeding strategies and management choices. For instance, it is clear that there is potential to reduce most environmental impact categories through diet formulation for the UK. For the results presented here, there was no way to minimise the impact of feed production for one impact category without adversely affecting another through diet formulation in the US, therefore it might be reasonable to suggest a multifaceted approach that targets more than one impact category at a time. Depending on environmental impact objectives, consideration of the effect of diets beyond GWP might be something to take into account. For non-ruminant production systems there is increasing concern regarding the associated EP and AP impacts (LEAP, 2015a). What this study emphasises clearly is that targeting GWP only is not necessarily a sustainable solution to mitigating the environmental impact of the poultry industry. Targeting GWP without taking other environmental impact categories into account can inadvertently be detrimental to environmental objectives. A multi-criteria approach to diet formulation methodologies which accounts for both environmental impact and economic constraints, such as the one presented here, will be crucial in efforts to improve the sustainability of livestock systems.

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